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The distinctive hiss of radio "noise" is familiar to all of us old enough to have listened to vintage a.m. radio shows and certainly to all those personnel who ever tried to "pull in" a weak signal during a tour in military communications. Indeed, virtually since the birth of the telephone and radio and extending to today's sophisticated telecommunications designs, engineers have devoted prodigious efforts to eliminating or minimizing the effects of noise. In consequence, an entire discipline, known as *linear* filter theory, has evolved and is familiar to every electrical engineering and/or communications student, usually as one or a set of rather rigorous courses. By contrast, this paper is concerned with a *nonlinear* filtering process known as *Stochastic Resonance* (SR), research on which has been supported by the Physics Division of the Office of Naval Research (ONR) for several years and more recently by the Cognitive and Neural Sciences Division of the ONR.

To those schooled in linear doctrine, filtering with SR begins with a most radical premise: that the noise, which may either be inherent or generated externally, can be used to *enhance* the flow of information through certain, carefully designed, nonlinear systems. SR has now been demonstrated in a variety of physical experiments ranging from ring lasers through various solid state devices including SQUIDs (superconducting quantum interference devices) to noise-driven chaotic attractors. Moreover, there is accumulating, though quite preliminary, evidence that nervous systems may have evolved in such a way as to make use of SR in the transmission and possibly also the processing of sensory information. Should this notion withstand the rigors of detailed scientific scrutiny, it would constitute the *discovery* of SR as a natural process as opposed to the demonstration of the phenomenon in experiments designed by man. This possibility is quite exciting, since it promises to teach us something fundamentally new. Moreover, it is not difficult to imagine what such a development would imply for the many signal processing applications of importance to the Navy. Readers who wish to learn more about this new field of study may consult the proceedings of a recent international conference devoted to SR and jointly sponsored by the ONR, NCCOSC-RDT&E Division and by NATO.

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NONLINEAR RESONANCE: NOISE-ASSISTED INFORMATION PROCESSING IN PHYSICAL AND NEUROPHYSIOLOGICAL SYSTEMS

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Introduction

The distinctive hiss of radio "noise" is familiar to all of us old enough to have listened to vintage a. m. radio shows and certainly to all those personnel who ever tried to "pull in" a weak signal during a tour in military communications. Indeed, virtually since the birth of the telephone and radio and extending to today's sophisticated telecommunications designs, engineers have devoted prodigious efforts to eliminating or minimizing the effects of noise. In consequence, an entire discipline, known as *linear* filter theory, has evolved and is familiar to every electrical engineering and/or communications student, usually as one or a set of rather rigorous courses. By contrast, this paper is concerned with a *nonlinear* filtering process known as *Stochastic Resonance* (SR), research on which has been supported by the Physics Division of the Office of Naval Research (ONR) for several years and more recently by the Cognitive and Neural Sciences Division of the ONR.

To those schooled in linear doctrine, filtering with SR begins with a most radical premise: that the noise, which may either be inherent or generated externally, can be used to *enhance* the flow of information through certain, carefully designed, nonlinear systems. SR has now been demonstrated in a variety of physical experiments ranging

from ring lasers through various solid state devices including SQUIDs (superconducting quantum interference devices) to noise-driven chaotic attractors. Moreover, there is accumulating, though quite preliminary, evidence that nervous systems may have evolved in such a way as to make use of SR in the transmission and possibly also the processing of sensory information. Should this notion withstand the rigors of detailed scientific scrutiny, it would constitute the *discovery* of SR as a natural process as opposed to the demonstration of the phenomenon in experiments designed by man. This possibility is quite exciting, since it promises to teach us something fundamentally new. Moreover, it is not difficult to imagine what such a development would imply for the many signal processing applications of importance to the Navy. Readers who wish to learn more about this new field of study may consult the proceedings of a recent international conference devoted to SR and jointly sponsored by the ONR, NCCOSC-RDT&E Division and by NATO[1].

The idea of SR is not difficult to understand. The basic requirement is for a bistable system (though other configurations are also admissible) which is most easily imagined by picturing an energy potential with two wells separated by a barrier such as the one shown in Fig. 1. Suppose that the ball shown near the bottom of the right hand well represents the state point of the system. Information is transmitted through the system in the form of switching events between the wells. The output is the coordinate $x(t)$, and our interest is only in whether $x(t) > 0$ or $x(t) < 0$ (that is, whether the ball is in the right or left well). Imagine that a weak, time-periodic input signal, for example a sinusoidal wave, is applied in such a way as to rock the potential as shown by the three images in Fig. 1, alternately raising and lowering each well in relation to the barrier. The signal is assumed to be "weak" in the sense that its amplitude is never sufficient by itself to cause the state point to switch wells. Thus, the signal by itself cannot cause information to flow through the system. Now consider that noise, in the form of a random, time dependent, horizontal force, is applied to the

ball. If the noise is distributed like, for example, a Gaussian, there will always be a non zero probability for a switching event to take place. Of course, the probability of a switching event becomes greatest when the state point is in the elevated well, so that it "sees" a barrier reduced in height separating it from the lower, or more stable, well. This condition occurs at the time when the signal is at a maximum, so that the probability of a transition is coherent with the input signal. In consequence, the sequence of switching events, while largely random, will also be coherent to some degree with the input signal. Information about the input signal is, therefore, manifest in the switching events which themselves occur only by virtue of the presence of the noise.

The statistical physics governing such processes (however, without external signals) was put forth over 50 years ago by H. A. Kramers[2]. The rate at which switching events take place, we call it the "Kramers rate", is given by

$$\omega_K = C\exp\left[-\frac{\Delta U_0}{D}\right], \tag{1}$$

where ΔU_0 is the barrier height, D is the noise intensity (the variance) and C is a constant which depends on the detailed shape of the potential and is of no interest to us here. The key point, and the single most important property of this formulation from a signal processing point of view, is that the Kramers rate is an *exponential* function of the instantaneous barrier height. This causes the rate to be extremely sensitive to small changes in the barrier height, and to transmit those changes to the output in the sequence of switching events. In the presence of the weak sinusoidal signal,

$$\Delta U_0(t) \rightarrow \Delta U_0 + f(\delta\sin\omega t), \tag{2}$$

and the Kramers rate becomes periodic, $\omega_K \rightarrow \omega_K(t)$. Thus, we can easily understand the exponential sensitivity of $\omega_K(t)$ on the signal strength, δ. The switching events can be thought of as sampling the input waveform at more-or-less random times. Obviously, in order for the output to convey a maximum amount of information about the input signal, the "sampling rate" must be sufficiently large. This means that the signal frequency should be small compared to the Kramers rate, $\omega \ll \omega_K$, a condition called the "adiabatic approximation" which is characteristic of most current statistical theories of SR. A modern theory of SR was first put forth by McNamara and Wiesenfeld[3]. Indeed, recent research in this laboratory (J.D. & F.M.) has shown that, just as is the case with digital signal processing, a Nyquist frequency, $\omega_N \equiv (1/2)\omega_K$, can be identified, which plays the role of a cutoff frequency in SR, just as it does when the waveform is periodically sampled in the more familiar way.

The output is thus a sequence of switching events between, for example, +1 and -1, as shown in Fig. 2(a). [We completely neglect the intra well motion and replace the raw output by a sequence of $\pm$ 1's denoting the well in which the ball is instantaneously confined.] The sequence of time intervals, T_0, T_1 ... T_i, identify the time intervals between like switching events, say from the -1 to the +1 well. Two objects can be assembled and averaged from such a time series, and from each a signal-to-noise (SNR) can be extracted. The first is the residence time probability density, P(T), which is a histogram of the residence times, T_i. An example histogram is shown in Fig. 2(b). Note the exponentially decaying sequence of peaks at all integer multiples of the signal period[4-6]. An SNR can be defined by counting the number of events in some narrow range centered on each peak, summing these for all peaks, and counting and summing all counts in the same range centered on each minimum between peaks. The SNR is formed from the ratio of the peak count to the valley count. The second object is more familiar. It is the power spectrum, an example of which, obtained from analog simulation, is shown in Fig. 2(c). This power

spectrum shows a sharp signal feature at the signal frequency (and other much weaker ones at the odd harmonics) riding on a Lorentzian background due to the noise. The strength, S (≡ the area under the peak) is obtained by locally integrating the neighborhood including the peak. The strength represents that fraction of the total number of switching events (or neural spikes) which are coherent in frequency with the signal (or stimulus). The incoherent fraction shows up in this spectrum as the fluctuating, wide band, Lorentzian background curve. The noise intensity, N, is given by the amplitude of this background at the base of the fundamental signal feature, i.e. the value of the noise background at the signal frequency. The SNR is then defined in the standard way familiar from communications engineering: $SNR = 10\log_{10}\left[\frac{S}{N}\right]$ in decibels (dB).

These two SNR's, of course, depend upon, and change with, the external noise intensity D. The essence of SR is the remarkable property that both SNR's attain maxima at specific values of D, that is, *there exists an optimal noise intensity which maximizes the transmission of information through the system*. An example of this behavior, which happens to have been obtained from an analog simulation of a simple single neuron model, is shown in Fig. 3.

Though the current applications of SR are very exciting, and consequently have stimulated a vigorous research enterprise currently in progress at various institutes scattered around the globe, the concept of SR is not new. We therefore begin this paper with a brief historical background. Though SR has been demonstrated in a variety of experimental settings, including the sensory, or peripheral, nervous system as indicated below, it has not been experimentally observed in collections of coupled neurons as are found in the central nervous system. In order to explore the feasibility of this possibility, we have included a section devoted to a unique theoretical approach to modeling the dendritic system with a set of coupled bistable systems. In this model, the important and interesting case of nonlinear coupling is treated for the first time.

This is followed by a section which describes an experimental search for SR in crayfish mechanosensory receptors. In addition, we discuss the results of an experiment designed to demonstrate SR in a bistable SQUID. We conclude with a summary of our research and discuss a number of speculative questions.

Historical Background

The mechanism of SR was first propounded by Vulpiani and his co workers[7] as an interesting stochastic effect in nonlinear dynamics which might have useful applications in a variety of fields. C. Nicolis[8], independently, and the aforementioned authors, together with Parisi[9], proposed SR, in 1982, as a possible explanation of the observed periodicities in the recurrences of the earth's ice ages. In this view, the earth's climate is represented by a one dimensional bistable potential, one (meta) stable state of which represents a largely ice covered earth[10]. The external noise is assumed to come from short term fluctuations in the balance between radiative and convective transport processes, and the periodic modulation is most often supposed to originate from variations in the insolation resulting from a small observed oscillation in the eccentricity of the earth's orbit having a period of 100,000 years[11].

In 1983, Fauve and Heslot made detailed measurements on a noise driven, periodically modulated, bistable electronic system (a Schmidt trigger)[12]. They measured the power spectrum of the output from which they extracted the SNR, and observed that this quantity passed through a maximum with increasing noise intensity, thus demonstrating SR for the first time in a laboratory experiment. The location of the maximum in the SNR was identified (roughly) with the specific value of the noise intensity for which the Kramers rate in the unperturbed potential becomes comparable to the modulation frequency. No theory was put forth by these authors. Instead, their experiment served to clearly demonstrate the observable, physical aspects of SR.